

各種形状物体をすぎる反射衝撃波の非定常遷移に関する研究

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論 文 内 容 要 旨

Abstract

The reflection of plane shock waves is one of important and fundamental topics, and has been investigated by many researchers. For the case of flows over a wedge, since the geometry has no any length scale, solutions of the inviscid conservational laws or the Euler equations must be some functions of the ratios of spatial variables and time. This kind of distinctive solutions is often referred to as self-similar one. Therefore the pattern of shock reflection is also self-similar or pseudo steady. von Neumann (1943) was able to develop the simple but powerful three-shock theory by taking the advantage of the self-similar assumption. The theory and self-similar assumption of shock reflection have been generally supported by laboratory experiment, so the self-similar assumption was believed to be correct for a few decades.

Until quite recently, Henderson et al. (1997) numerically clarified that due to viscosity and thermal conductivity effects, the pattern of shock wave reflection over a wedge could be not self-similar at the early stage of reflection. Given a shock wave and a wedge angle that should form a Mach reflection according to von Neumann's three shock theory, they found a regular reflection first appears near the leading edge, and as the incident shock wave propagates, the precursory regular reflection pattern is swept away by an overtaking corner signal that forces the transition to Mach reflection. Because viscosity and heat conductivity are dominating near the leading edge, corner signal cannot catch up with the incident shock there, so that a regular reflection appears instead. As incident shock wave propagates, influence of viscosity and heat conductivity is weakened and the corner signal starts to overtake the incident shock. Finally a transition from regular reflection to Mach reflection happens, and then the reflection pattern

gradually approaches self-similar one again. This process is called delayed transition. Because the distance from the corner to the location where the Mach reflection first appears is usually very short, the delayed transition phenomenon was neglected or disregarded in early experiments.

In experiment, by choosing shock strength and wedge angle that theoretically form a Mach stem very close to the wedge surface, Itabashi et al. (1997) successfully records both the pattern of the regular reflection close to the leading edge and the pattern of the Mach reflection some distance way on one photo, and confirmed that viscosity and the thermal conductivity did affect the self-similarity. The present thesis aims to systematically investigate effects of viscosity and heat conductivity on the delayed transition over wedges, cones, and curved wedges numerically and experimentally.

In numerical simulation, a vectorized adaptive solver for two spatial variables (VAS2D) that was developed by Sun at the Shock Wave Research Center is selected as a start point. The VAS2D is a finite volume solver using solution-adaptive quadrilateral mesh, and allows automatic vector and parallel processing on supercomputer. The VAS2D can be easily modified for different geometry, therefore it is very suitable for pressure research. The original VAS2D flow solver uses a central-difference scheme, and possible numerical oscillations are suppressed by a delicate smoothing technique. In order to reproduce more precise and more reliable flow patterns numerically, a new flow solver using the upwind idea is implemented to the VAS2D architecture. In this new flow solver, the MUSCL-Hancock scheme is extended to unstructured quadrilateral grid, and the exact Riemann solver, HLL and HLLC approximate Riemann solvers are constructed. The MINMOD slope limiter is generally used to avoid overshoot in data reconstruction. In mesh adaptation, directional refinement is utilized to improve efficiency in resolving viscous flow near a wall inside the boundary layer. The flow solvers and direction refinement technique are validated by simulating the steady laminar compressible flow over a flat plate. It is shown that both wall friction and profiles of velocity and density that obtained by numerical simulation agree very well with theoretical predictions.

We simulate pseudo flow over the wedge to find mechanism of a delayed transition using numerical simulation described above (VAS 2D). We successfully found out this mechanism. Mitobe et al. conducted these experiments continuously and they successfully recorded that for the case of nitrogen, the delayed transition from regular reflection to Mach reflection also appears on the same wedges. A self similarity which was believed for a long time should be ceased by replacing the fact that there is a delayed transition from regular reflection to Mach reflection on the same wedge from their idea which comes from their experiments. It is also confirmed that it is happened not only in a monatomic molecule, but also in a diatomic molecule.

We considered two different parameters for these experiments, namely different initial pressures (Reynolds number effects) with fixed wedge angle and different wedge angles with fixed initial pressure.

For the case of initial pressure change, hence, by changing Reynolds numbers, at the high Reynolds number, there is a smaller length of transitional delay compared with low Reynolds number. The reason for this is as follows;

Mach stem height in the high Reynolds number is higher than that of the low Reynolds number. At high Reynolds number (high initial pressure), thickness of the boundary layer is thinner than that of low Reynolds number, then, gradient of the negative displacement thickness is relatively low. Hence corner generated signal can easily catch up with the reflection point and length of transitional delay should be smaller and then height of Mach stem is high in early stage of the shock reflection in high Reynolds number flows.

Next parameter is the wedge angle. Below the detachment criterion, the agreement between experiment and three shock theory are very well. It seems that transition angle between regular reflection and Mach reflection is mechanical equilibrium criterion. However, when the angle is between detachment criterion and mechanical equilibrium criterion, suddenly length of transitional delay becomes zero; no Mach reflection occurs. From these facts, it is known that transition criterion from regular reflection to Mach reflection is on the detachment criterion (sonic criterion).

In the case of cone, by changing cone wedge angle, length of transitional delay is longer than that of the wedge. This is the three-dimensional effect. Flow variable will be changed as shock wave propagate to the cone wedge by $1/r$. During this process, pressure perturbation attenuate along the cone wedge.

On the other hand, the propagation of the shock reflection over convex and concave wedges does not show self-similar state and are truly unsteady flow. The effect of radius of curvature on the transition angle and triple point trajectory has reported, but the effect of viscosity and thermal conductivity on ones has not been done. The objective is to investigate the effect of the viscosity on shock wave reflections over convex (diameter = 50mm) and concave wedges (diameter = 200mm) experimentally and numerically.

In order to see viscous effect under different Reynolds number, reflection over a smaller convex model with diameter 50 mm have also been conducted. Experimental photograph are obtained by double exposure holographic interferometry. it can be concluded that because of viscous effect, delayed transition from Mach reflection to regular reflection is seen. There is a Reynolds number dependence in critical angle. This clearly indicates that viscous effect influence on transition from Mach reflection to regular reflection over concave wedges. The difference between experiment and simulation is possibly due to roughness of the surface of

the concave model.

Finally, by rotating cylinder, different velocity distribution for incident Mach number exists. Furthermore, there is no change of shape for the rotation. The objective is to see the transition of non-stationary flow with a different velocity distribution on upper side and lower side of the cylinder. Then, to find transition mechanism for non-stationary flows. Rotating direction is clockwise. Both experiment and numerical simulation, it is found that on upper side, since corner signal speed is promoted by rotation, Mach stem is higher than that of lower side. On the other hand, on lower side, as corner signal speed is prevented by opposite direction of rotating direction, Mach stem is not so high as that of upper side.

At last, the conclusions are summarized as follows. The upwind scheme using the exact and approximate Riemann solvers are implemented into the VAS2D and its high accuracy has been proven by analyzing the flat plate flow. By combining high-resolution visualization technique and powerful numerical tool, it is found that the delayed transition from regular reflection to Mach reflection or Mach reflection to regular reflection appears over different geometry, and this process has been quantitatively measured. It is confirmed that the idea of corner signals can qualitatively interpret the delayed transition over different shape of walls.

審査結果の要旨

衝撃波工学および気体力学の分野では物体周りの衝撃波の非定常な挙動の解明は重要な研究課題で、特に、種々の物体形状からの反射衝撃波が遷移する現象には多くの未解決の問題を残している。一方、最近の数値シミュレーション法の進歩および計測技術の発展によって、これらの現象を定量的に解明する手段を確立する気運が高まっている。本論文は、これらの研究の発展を背景に反射衝撃波の非定常な遷移現象を精緻な数値解析でまた実験手法を駆使して解明した結果をとりまとめたもので、全編5章からなる。

第1章は緒論である。

第2章では、気体の粘性効果による反射衝撃波の遷移遅れを数値的に実証するために、二次元ベクトル化解適合数値解法を用いてその有用性と精度を論じ、特に層流平板境界層を例にとり、境界層内の格子の非等方細分化の取り扱いについて詳細に検証している。

第3章では、くさび、円錐、凹面および凸面を過ぎる反射衝撃波の遷移遅れを、再現性のよい無隔膜衝撃波管を用い空間解像に優れた光学可視化法を採用する実験で詳細に論じている。また、その結果と第二章において検証した数値解析法を用いた結果とを対比してよい一致を導いている。以上のことから、反射衝撃波の遷移遅れは、単原子気体ばかりでなく二原子分子気体にも現れ、気体の粘性効果に起因する普遍的な現象であることを示し、さらに、くさび、円錐を過ぎる準定常流ればかりでなく凹面および凸面を過ぎる非定常流れにも起こり、反射衝撃波の形態は必ずしも自己相似性を保たないことを見い出している。これは空気力学の教科書を書き直すに値する発見である。

第4章では、遷移遅れは反射衝撃波背後の擾乱伝播の機構に支配されることを、比較的高速回転する円筒を過ぎる平面衝撃波の反射形態にその上下面で顕著な遅れの差を現すことを無隔膜衝撃波管実験で、また第二章に述べた数値解法を用いて実証している。これは独創的な着想に基づく現象解明法で、評価に値する。

第5章は結論である。

以上要するに本論文は、非定常な反射衝撃波の遷移に及ぼす粘性効果を詳細に明らかにしたもので、衝撃波工学、気体力学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。